Managing Arrhythmias in the Intensive Care Unit

Cynthia Tracy, MD[a,*], Ali Boushahri, MD[b]

KEYWORDS

• Cardiac arrhythmia • Intensive care unit • Tachyarrhythmia • Bradyarrhythmia

KEY POINTS

- Patients admitted to the intensive care unit (ICU) are at increased risk for cardiac arrhythmias.
- Cardiac arrhythmias are common in the ICU, and can be either the initial reason for admission to the ICU or a consequence of the medical condition.
- Exacerbating and contributing factors are multiple, and management of the patient requires a careful determination of these factors and correction where possible.

INTRODUCTION

Patients admitted to the intensive care unit (ICU) are at increased risk for cardiac arrhythmias, which may be either the primary reason for ICU admission or a contingency in the critically ill patient. This article addresses the occurrence of arrhythmias in the critically ill patient, and their pathophysiology, implications, recognition, and management.

PATHOPHYSIOLOGY

Although patients can be admitted to the ICU with a variety of conditions, the critical nature of their underlying processes and the supportive measures used to treat them can contribute to an elevated catecholamine state. Coupled with fluctuations in intravascular volume, electrolyte disturbances, and other metabolic derangements, this places patients at risk for cardiac arrhythmias. The incidence of arrhythmia in the ICU patient can approach 40%, most typically associated with conditions such as septic shock and respiratory failure.[1] The most common arrhythmias in the ICU setting can be divided into 2 basic categories: (1) tachyarrhythmias (eg, atrial fibrillation [AF] and atrial flutter, ventricular arrhythmias, and other supraventricular tachycardias [SVTs]) and (2) bradyarrhythmias (eg, junctional rhythm, sinus bradycardia, and atrioventricular [AV] conduction block).

[a] Department of Medicine, George Washington University, 2150 Pennsylvania Avenue, Northwest, Washington, DC 20037, USA; [b] Cardiovascular Medicine, George Washington University, Medical Faculty Associates, 2150 Pennsylvania Avenue, Northwest, Washington, DC 20037, USA
* Corresponding author.
E-mail address: ctracy@mfa.gwu.edu

Crit Care Clin 30 (2014) 365–390
http://dx.doi.org/10.1016/j.ccc.2014.03.009 **criticalcare.theclinics.com**
0749-0704/14/$ – see front matter © 2014 Elsevier Inc. All rights reserved.

SHOUT
SHARE
IT

Predictors of tachyarrhythmia occurrence in ICU patients include the use of stimulant drugs such as norepinephrine, and a high APACHE II score (≥25) (see the article on Cardiogenic Shock by Shah and colleagues elsewhere in this issue). For those with bradyarrhythmias, identified predictors include the use of norepinephrine (which is a predictor of both tachyarrhythmia and bradycardia), arterial pH less than 7.3, and HCO_3 level of 18 mEq/L or higher (see **Box 1** for common risk factors).[1]

CONSEQUENCES OF ARRHYTHMIAS IN THE INTENSIVE CARE UNIT

The presence of arrhythmia, especially ventricular fibrillation (VF), symptomatic sinus bradycardia, and junctional bradycardia, in the medical ICU has been associated with higher in-hospital mortality. Tongyoo and colleagues[1] reported on a single-center population of 247 ICU patients (mean age 58.5 years; mean APACHE II score 20.1). In this group of critically ill patients, arrhythmias were seen in 39.7%. The mortality among patients who developed arrhythmias was significantly higher than among those who did not. Among those who developed significant bradyarrhythmias (sinus or junctional) the mortality was 88.7%, and in those with tachyarrhythmias (particularly VF) the mortality was 66.7%, compared with 18.1% mortality (P<.001) in patients free of arrhythmias.

Similar results were seen by Annane and colleagues[2] among 1341 medical ICU patients, sustained arrhythmias being seen in 12% of patients. In this population, in-hospital death rates were 17% in patients without arrhythmia; 29% in patients with supraventricular arrhythmia (SVA); 73% in patients with ventricular arrhythmia (VA); and 60% in patients with conduction abnormalities.

The occurrence of arrhythmias in the ICU population can be associated with a prolonged stay in hospital.[3] Polanczyk and colleagues[3] reported on 4181 patients aged 50 years or older who presented in sinus rhythm and underwent nonemergency, noncardiac procedures. In this group of patients, perioperative SVAs were seen in in 317 patients (7.6%). Independent preoperative correlates for the occurrence of these arrhythmias included male sex, age 70 years or older, history of valvular heart disease or heart failure, and prior history of SVA or asthma. The occurrence of SVA was associated with a 33% increase in length of stay after adjustment for other clinical data (P<.001).

Goodman and colleagues[4] reported on both short-term and long-term consequences of arrhythmias in the ICU population. This study included 611 patients

Box 1
Risk factors for arrhythmia in the intensive care unit

- Male gender
- Age greater than 70 years
- Cardiac disease (coronary artery disease, heart failure, valvular disease)
- Pulmonary disease (asthma)
- Thyroid disease
- Critically ill (APACHE score ≥25)
- Volume fluctuations
- Electrolyte disturbances
- Metabolic derangements
- Vasopressors

admitted to the general ICU who were evaluated for the development of SVA. Patients were followed through hospital discharge, and 48-month mortality was evaluated. New-onset SVA was found in 9% of patients, and preexisting history of SVA in 12%. In-hospital mortalities were 18% in those with no SVA, 56% in the new-onset SVA group, and 32% in those with prior histories of SVA ($P<.05$ for any SVA vs no SVA; $P<.05$ for history SVA vs new-onset SVA). Similarly to other studies, mortality was associated with high APACHE II scores, sepsis, acute renal failure, and myocardial ischemia. For those with new-onset SVA the APACHE II score was 23.8 ± 8 versus 16 ± 8 for those without SVA ($P<.05$).[4] Of note, for those surviving to discharge the postdischarge mortality rates were 20% in the no-SVA group, 36% in the new-onset SVA group, and 45% in the history of SVA group ($P<.05$ for any SVA vs no SVA; $P<.05$ for history SVA vs new-onset SVA). Most deaths in the new-onset SVA group occurred during the acute hospital stay and were typically associated with multiorgan system failure as reflected in the APACHE II scores.[4] Moreover, in this study new-onset SVAs were not found to be associated with a preadmission history of cardiac disease, being more closely associated with a history of underlying pulmonary disease and hypothyroidism.

DIAGNOSTIC APPROACH

Determine Urgency

As in any other patient population, the management of arrhythmias in the ICU patient is determined by the acuity of the problem (**Box 2**). An initial critical step is determining whether an arrhythmia truly exists, or if an artifact is recorded as a result of electrical interference created by devices in the patient environment, or is created by motion (**Fig. 1**). If an arrhythmia is confirmed, the urgency of treatment will depend on a determination of whether the rhythm itself is causing compromise to the patient. Management will be more urgent in the setting of an acute arrhythmia that is resulting in symptomatic hypotension and/or hypoperfusion to vital organs.

Identify Causes

Regardless of whether urgent steps are required, identification of correctable underlying causes should be undertaken when the patient is sufficiently stabilized (**Box 3**). Multiple electrolytes and acid-base abnormalities are common in the ICU patient population, and in one study were reported in around 67% of patients.[5] Hypokalemia is a well-recognized contributor to cardiac arrhythmia, and in the population with ischemic heart disease the likelihood of VF as almost twice as high among patients with potassium levels of less than 3.6 mEq/L as in those with higher levels (odds ratio 1.97).[6,7] In up to 40% of patients with hypokalemia there is concomitant hypomagnesemia, and unless this is corrected it may not be possible to correct the potassium level.[8]

Box 2
Determinants of urgency

- Hypotension
- Ischemia
- Heart failure
- Altered mentation
- Other signs of hypoperfusion: hypoxia, decreased urine output

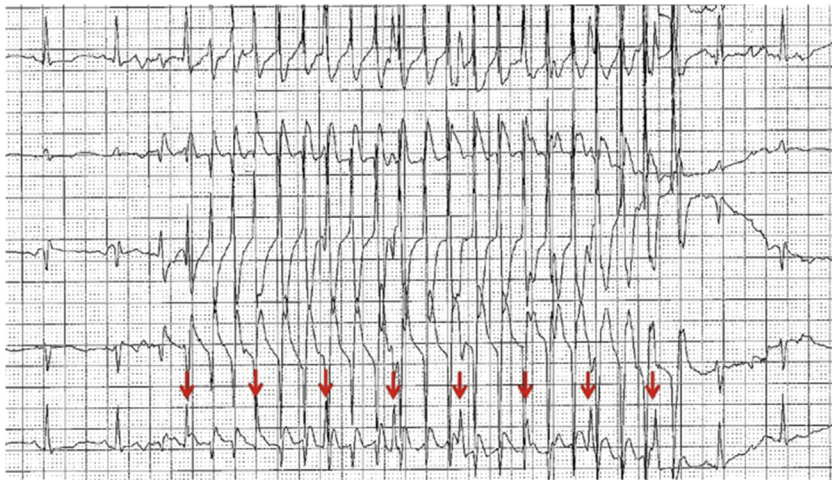

Fig. 1. Telemetry strip demonstrating artifact initially thought to be ventricular tachycardia. Close examination reveals underlying sinus rhythm with motion artifact (*arrows* indicate QRS complexes).

The relation between potentially life-threatening arrhythmias and inappropriate ventilation, hypoxemia, hypo- or hyperventilation, and metabolic acidosis has long been appreciated.[9] Patients in the ICU are at risk for these potentially reversible causes of arrhythmias. Critically ill patients are with volume overload can be arrhythmogenic because of atrial stretch.[10] In patients with an indwelling catheter such as a peripherally inserted central catheter or other central line, mechanical stimulation may lead to arrhythmias.

Advanced Cardiac Life Support (ACLS) guidelines emphasize the "5 H" and "5 T" reversible causes of arrhythmias applicable in all clinical scenarios: Thrombosis, pulmonary/cardiac; Tension pneumothorax; Tamponade, cardiac; Trauma; Toxins; and Hypoxia; Hydrogen ions (acidosis); Hypothermia; Hypovolemia; Hypo-/Hyperkalemia.[11] Care should be taken in the ICU patient to prevent or correct these potential

Box 3
Causes of arrhythmia

- Hypoxia/hypoventilation
- Hypovolemia/hypervolemia
- Electrolyte imbalances (potassium, magnesium)
- Metabolic acidosis
- Hypothermia
- Coronary ischemia
- Cardiac tamponade
- Acute pulmonary process (pulmonary embolism, pneumothorax)
- Trauma
- Intoxication
- Mechanical stimulation (central line)

causes and contributors to arrhythmias. Without correction, management of the arrhythmia may not be possible.

UNDERSTANDING MECHANISMS OF ARRHYTHMIAS

An understanding of the basic mechanisms of cardiac arrhythmias is helpful in determining correct therapeutic approaches.

Bradyarrhythmias

Bradyarrhythmias (Table 1) arise from problems in impulse generation (automaticity) and/or impulse conduction (heart block). Diminished automaticity in the sinus node results in sinus bradycardia, and in more extreme cases sinus pauses. Heart block is usually due to disease (more commonly fibrosis, less commonly ischemia) in the AV node or His-Purkinje system, the latter being associated with higher grades of AV block. The degree of heart block is determined by the extent of impulse conduction from the atria to the ventricles: in first-degree heart block all impulses are conducted, albeit at a slower rate (prolonged PR interval); in second-degree heart block they are intermittently conducted; and in third-degree heart block none of the atrial impulses are conducted. Bradyarrhythmias can be seen in a variety of settings in the ICU, such as with elevated intracranial pressure, exaggerated vagal activity (coughing, vomiting), carotid sinus pressure (tight collar), hypothyroidism, hypothermia, ischemia, metabolic abnormalities (hyperkalemia), and various drugs (β-blockers, calcium-channel blockers, antiarrhythmics, digoxin, clonidine, opioids, lithium, dexmedetomidine).[12]

Tachyarrhythmias

Tachyarrhythmias (Table 2) have 3 general mechanisms: increased automaticity, reentry, and triggered activity. Enhanced automaticity can occur in the atrium, AV node, or within the ventricle. These automatic foci in the atria, AV junction, or ventricles can accelerate and drive an ectopic tachyarrhythmia, such as paroxysmal atrial tachycardia. Automatic tachyarrhythmias (both atrial and ventricular) are commonly encountered in the ICU, as they are triggered by metabolic disturbances such as electrolyte abnormalities (namely potassium and magnesium disturbances), acid-base disturbances, hypoxemia, and ischemia. Use of vasopressors and inotropes can also contribute, given their sympathomimetic properties.

Reentry

Reentry is the most common mechanism for tachyarrhythmias. For reentry to occur, 2 pathways (or tissue) with different conduction properties must exist and be anatomically oriented in such a way as to form an electrical circuit. These circuits may be congenital (eg, dual AV node) or acquired (surrounding or within scar tissue of uneven electrical properties). As such, reentry can occur around anatomic barriers such as scar, or by utilizing anatomically distinct pathways such as the slow and fast pathways of the AV node. Reentrant arrhythmias are often provoked by premature complexes arising in either the atrium or the ventricle. A well-timed electrical impulse takes

Table 1
Bradyarrhythmias

Mechanism of Bradyarrhythmia	Examples
Decreased automaticity	Sinus bradycardia Sinus pause/arrest
Impaired conduction	Heart block (first, second, and third degree)

Table 2
Tachyarrhythmias

Mechanism of Tachyarrhythmia	Examples
Increased automaticity	Paroxysmal atrial tachycardia Multifocal atrial tachycardia
Reentry	Atrial flutter Atrioventricular (AV) nodal reentrant tachycardia AV reentrant tachycardia Ventricular tachycardia
Triggered activity	Digoxin toxicity Torsades de pointes

advantage of the discrepancies in conduction properties, penetrating one limb of the circuit while the second is refractory owing to the prematurity of the stimulus. The impulse travels forward on the anterograde limb, and can then proceed retrograde up the second pathway of the reentrant loop, which will now have recovered its ability to conduct. The impulse can create an endless loop of reentry while simultaneously activating adjacent myocardium. Perpetuation of the circuit depends on the ability of both limbs to maintain the tachycardia (Fig. 2). Common reentrant arrhythmias encountered in the ICU, as well as other clinical settings, include AV nodal reentrant tachycardia (AVNRT), atrial flutter, and ventricular tachycardia (VT). AV reentrant tachycardia (AVRT) is less frequently seen, and depends on the substrate (accessory pathway, as in Wolff-Parkinson-White [WPW] syndrome) being present. Reentry is favored when there is differential conduction in the two limbs or the circuit and this is favored by changes in heart rate and autonomic tone,[13] ischemia, and pH and electrolyte abnormalities.

Triggered activity

Triggered activity involves the premature activation of the cardiac cell during the repolarization (recovery) period, which is referred to as an afterdepolarization. These

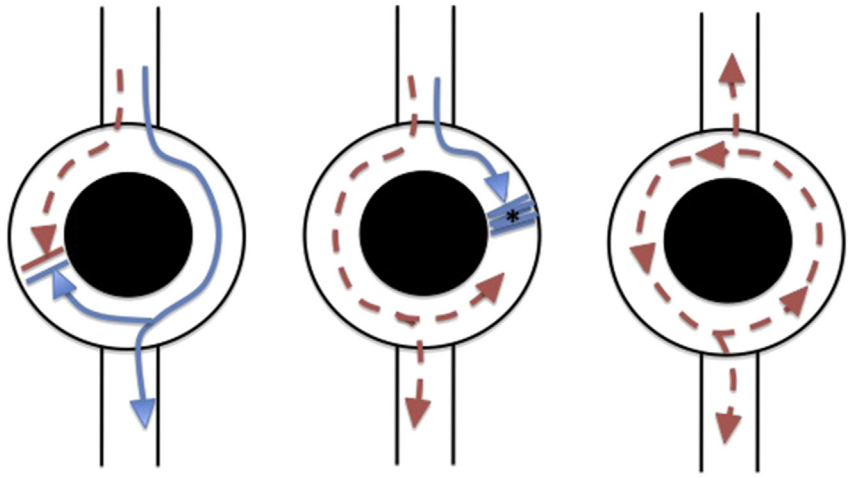

Fig. 2. There are 3 necessary components for reentry to occur: (1) 2 separate pathways, (2) unidirectional block in 1 pathway (*asterisk*), and (3) slow conduction along the other pathway. To persist, both pathways must be capable of maintaining conduction.

afterdepolarizations are capable of sustaining a tachyarrhythmia and are the likely underlying mechanism in certain rhythms. Digoxin has been implicated in the occurrence of delayed afterdepolarizations, which likely are at least partly responsible for the various tachyarrhythmias seen in the setting of digoxin toxicity (such as paroxysmal atrial tachycardia with block).[14] Triggered activity has also been implicated in the pathogenesis of torsades de pointes, whereby early afterdepolarizations in the setting of a prolonged QT interval can precipitate polymorphic VT (PMVT). The prolonged QT interval can be congenital or acquired, as in the setting of numerous drugs (including antiarrhythmics, antimicrobials, antihistamines, and psychotropics),[15,16] metabolic abnormalities (hypokalemia, hypomagnesemia, hypocalcemia), ischemia, and hypothermia. PMVT in the setting of acquired long QT is usually pause dependent, and is precipitated by long-short RR intervals.[17]

DIAGNOSIS AND MANAGEMENT OF SPECIFIC ARRHYTHMIAS ENCOUNTERED IN THE ICU

Atrial Fibrillation

AF is the most common sustained arrhythmia in the general population, and occurs in up to 31% of ICU patients (**Fig. 3**).[18] Risk factors for AF include: advancing age (≥33% of patients with AF are ≥80 years); presence of structural heart disease; and chronic conditions: cardiac (eg, hypertension) and noncardiac (eg, renal failure, chronic obstructive pulmonary disease).[19,20] Risk factors for AF in the ICU setting include hypotension, use of vasopressors or inotropes, septic shock, fluid overload, electrolyte imbalance, heart failure, and postoperative status, among others (**Box 4**).[21] Mechanisms causing and sustaining AF are multifactorial, and AF can be complex and difficult for clinicians to manage. In the structurally normal heart variations in autonomic tone have been implicated in the initiation of AF, as surges in vagal and sympathetic tone have been detected in the minutes that precede initiation of the arrhythmia.[22,23] AF is associated with a 5-fold increased risk of stroke,[24] 3-fold increased risk of heart failure,[25–27] and 2-fold increased risk of mortality.[24] In the United States, AF alone contributes to nearly 10,000 deaths per year.

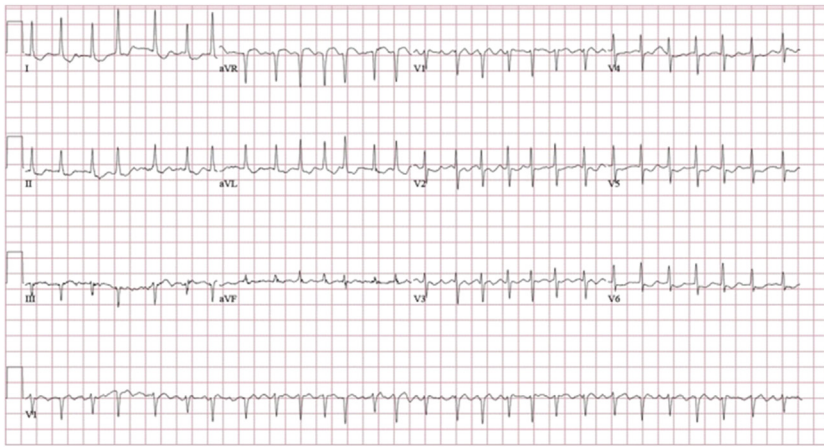

Fig. 3. Typical appearance of atrial fibrillation with rapid ventricular response. ST-segment changes are noted, which were not previously seen during sinus rhythm, and likely reflect demand ischemia.

Box 4
Predisposing factors for atrial fibrillation in the intensive care unit

- Advanced age
- Structural heart disease
- Chronic cardiovascular conditions (hypertension)
- Chronic noncardiac conditions (renal failure, chronic obstructive pulmonary disease)
- Hypotension and shock
- Fluid overload
- Electrolyte imbalances
- Vasopressors and inotropes
- Postoperative state

In AF there is loss of (or diminished) atrial contribution to ventricular preload, which accounts for 25% of ventricular end-diastolic volume in the normal heart.[28] Though of little consequence in the normal heart, this may become hemodynamically significant with systolic dysfunction, diastolic dysfunction (noncompliant ventricle), and rapid heart rates (decreased ventricular filling).

The acute management of AF involves 3 strategies: rhythm control (cardioversion), rate control, and anticoagulation. Cardioversion can be accomplished electrically or pharmacologically. Immediate electrical direct current (DC) cardioversion is indicated in patients with AF who have severe hemodynamic compromise (eg, hypotension, decompensated heart failure) thought to be related to the arrhythmia. If tolerated, premedication with a benzodiazepine or opiate is preferable. Shocks should be synchronized with the QRS complex. In general, pads placed anterior to posterior provide greater efficacy than do anterior and lateral positioning, and a biphasic waveform typically requires less energy than a monophasic waveform. If a single shock fails to result in conversion to sinus rhythm, repositioning pads, applying pressure over the anterior pad (to reduce impedance), and using a bipolar waveform may facilitate cardioversion.[29,30] DC cardioversion should not be attempted in the setting of digoxin toxicity or uncorrected hypokalemia.

Pharmacologic cardioversion may be appropriate in patients who are not immediately hemodynamically compromised and not experiencing cardiac ischemia as a result if the arrhythmia. Several antiarrhythmic agents are available, and the choice of drug will depend on the underlying myocardial function, but ibutilide and amiodarone are most commonly chosen in the ICU (**Table 3**). Intravenous ibutilide has a reported success rate of up to 50%, but has not been specifically tested in the ICU population.[31] Given its effects on repolarization, ibutilide can significantly prolong

Table 3
Dosing for atrial fibrillation pharmacologic cardioversion

Medication	Dose
Ibutilide	<60 kg: 0.01 mg/kg intravenously (IV) over 10 min ≥60 kg: 1 mg IV over 10 min May repeat once if arrhythmia does not terminate
Amiodarone	150 mg IV over 10 min, then IV drip 1 mg/min for 6 h followed by 0.5 mg/min for 18 h (total 1.05 g over 24 h)

the QT interval and provoke torsades de pointes, which has been reported in up to 3.9% of cases.[32,33] The risk of torsades de pointes is higher (and should therefore be avoided) in patients with heart failure, prolonged QT interval at baseline, or hypokalemia.[34] Ibutilide can facilitate electrical cardioversion, but this has not been specifically tested in the ICU setting.[35] Amiodarone is often the preferred agent in the ICU setting, particularly in patients with depressed ejection fractions given its better safety profile in this population. In the acute setting, amiodarone may provide rate control and can be used for longer-term rhythm control, as it has been shown to decrease AF recurrence.[36,37]

More than 50% of episodes of AF convert spontaneously without specific antiarrhythmic intervention within the first 72 hours,[38] and cardioversion may not be necessary unless symptoms are distressing. Management of AF in the hemodynamically stable patient focuses on adequate control of ventricular rate, and management of the underlying cardiac substrate and any coexisting conditions that could be contributing to the arrhythmia. In the ICU setting where ongoing illnesses may dominate the clinical picture, maintenance of sinus rhythm after cardioversion may be impossible even with antiarrhythmic medications, and a strategy of rate control may be needed.[39,40]

Acute rate control can be achieved with numerous drugs (**Table 4**). β-Blockers are particularly effective when adrenergic/sympathetic tone is elevated, such as in the postoperative period. Metoprolol may be initiated as intravenous boluses (up to 15 mg total within a 15-minute period) and followed by oral doses when rate control is achieved. The short half-life of intravenous esmolol makes it a good option in patients at risk for hemodynamic instability. In patients who cannot tolerate β-blockers or do not achieve adequate ventricular rate control, nondihydropyridine calcium-channel blockers such as diltiazem or verapamil may be used. However, calcium-channel blockers should be avoided in patients with heart failure and reduced ejection fraction, given their negative inotropic effects and potential to worsen hemodynamics. Alternatively, digoxin may be considered for use in patients with heart failure and marginal blood pressures. It should be used cautiously in patients with renal insufficiency, and has a relatively delayed onset of action (at least 1 hour), which is why it is not usually a first-line agent for rate control. Amiodarone may also cause slowing of the ventricular rate via its β-blocking and calcium-channel–blocking effects, and may provide better rate control than other agents.[41]

Magnesium has been shown to prevent the development of AF in some instances, and may have a synergistic effect when used with amiodarone for the suppression of AF.[42] A combination of the aforementioned drugs may be used if a single class is

Table 4
Drugs for rate control in atrial fibrillation

Medication	Dose
β-Blockers	
Metoprolol	2.5–5 mg IV over 2–5 min (up to 15 mg in 15 min)
Esmolol	0.5 mg/kg IV over 1 min, then IV drip 50–200 μg/kg/min
Calcium-Channel Blockers	
Diltiazem	0.25 mg/kg IV over 2 min, then IV drip 5–15 mg/h
Verapamil	0.075–0.15 mg/kg IV over 2 min
Digoxin	0.25 mg IV every 2 h (up to 1.5 mg in 24 h)
Amiodarone	150 mg IV over 10 min, then IV drip 1 mg/min for 6 h followed by 0.5 mg/min for 18 h (total 1.05 g over 24 h)

unable to adequately control the ventricular rate, but these patients must be very closely monitored because they are at increased risk for cumulative adverse effects, namely bradycardia and heart block.

In patients with WPW syndrome and AF, β-blockers should be used with caution, as they may facilitate anterograde conduction down the accessory pathway.[43] In AF with preexcitation, intravenous procainamide or ibutilide may be used to restore sinus rhythm.[44] However, intravenous amiodarone, adenosine, digoxin, or nondihydropyridine calcium-channel antagonists may accelerate the ventricular rate, and these drugs should be avoided.[45]

Postoperative AF is reported in 30% to 40% of patients undergoing coronary artery bypass surgery and in 60% of patients undergoing valve surgery, and usually appears in the first 4 postoperative days.[46] Risk factors include valvular surgery, advanced age, and failure to resume β-blocker therapy after surgery. β-Blockers are preferred for rate control of AF in this setting.[47] This arrhythmia is usually self-limited, and more than 90% of patients will convert to sinus rhythm within 6 to 8 weeks.[48]

Strategies for anticoagulation in general are based on the risk of embolization in the individual patient. This risk is generally calculated according to known risk factors for systemic embolization as described in the CHA_2DS_2-VASc score classification of risk (**Table 5**).[49] The annual risk for stroke is based on the total score calculated based on identified risk factors (**Table 6**).[50] In general, for patients with prior stroke, TIA, or CHA_2DS_2-VASc score of 2 or higher, oral anticoagulants are recommended. Oral anticoagulant options include warfarin, dabigitran, apixiban, and rivaroxiban.[51–54] The decision to anticoagulate any patient must be weighed against the risk of bleeding. In the general population, the HAS-Bled score can be calculated, with 1 point ascribed to risk factors for bleeding including hypertension, abnormal liver or renal function, history of stroke or bleeding, labile international normalized ratios, elderly age (>65 years), use of drugs that promote bleeding, or excess alcohol. Patients with a HAS-Bled score of 3 or greater are considered to be at high risk for bleeding while anticoagulated.[55] Patients in the ICU may be at particular risk for bleeding because of their underlying medical conditions, polypharmacy, and altered metabolism; in general, if anticoagulation is deemed necessary based on the CHA_2DS_2-VASc score, extreme caution should be used.

Atrial Flutter

Although the two are often seen in the same patient, atrial flutter is an arrhythmia distinct from AF. The incidence of atrial flutter is lower than that of AF in the ICU

Table 5
CHA_2DS_2-VASc score classification of risk

CHA_2DS_2-VASc Clinical Predictor	Score
Congestive heart failure, decreased ejection fraction	1
Hypertension	1
Age ≥75 y	2
Diabetes mellitus	1
Vascular disease (prior myocardial infarction, peripheral arterial disease)	1
Stroke/transient ischemic attack	2
Age 65–74 y	1
Sex: female	1
Maximum potential score	9

Table 6
Stroke risk stratification associated with CHA_2DS_2-VASc score

CHA_2DS_2-VASc Score	Adjusted Stroke Rate (%/y)
0	0
1	1.3
2	2.2
3	3.2
4	4.0
5	6.7
6	9.8
7	9.6
8	6.7
9	15.2

population, and in the study by Reinelt and colleagues[18] atrial flutter accounted for 3.6% of arrhythmia episodes. Management concerns and anticoagulation for atrial flutter are similar to those for AF. It can be more difficult to achieve rate control in atrial flutter than in AF, because fewer wavefronts penetrate the AV node in flutter in comparison with fibrillation, resulting in less suppression of AV-node conduction in flutter.[56] However, drug management is similar to that already described.

Atrial flutter is a macro-reentrant arrhythmia that registers a sawtooth pattern on the electrocardiogram (ECG) (**Fig. 4**). Typical flutter involves a macro-reentrant loop in the right atrium traversing from inferior to superior, resulting in negative waves in the inferior leads and positive flutter waves in V1. Atrial rates in typical flutter range from 240 to 300 beats per minute.[57] The degree of AV block varies, and with rapid A to V conduction the rhythm may be more difficult to determine until AV block is achieved with medication. In the ICU setting where sympathetic tone can be high or where sympathomimetic drugs are in use, ventricular rates may be rapid, as these situations favor enhanced AV conduction. Adenosine can facilitate unmasking of the underlying flutter waves. Adenosine results in transient block in the AV node but does not affect the flutter circuit itself. As with AF, adenosine should not be used in any case where there

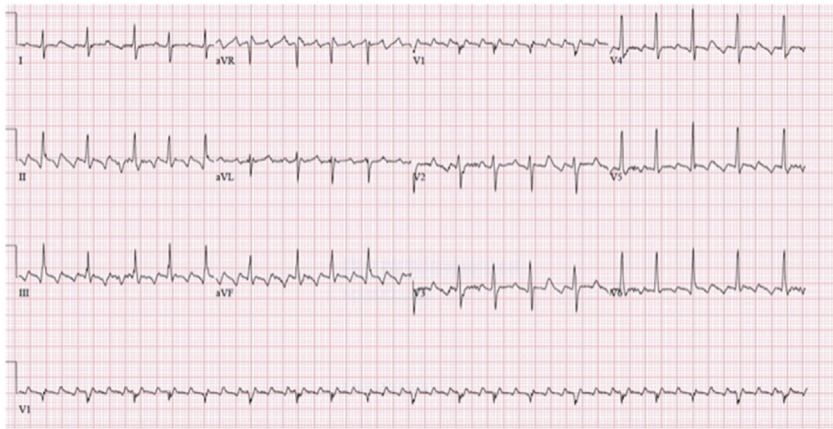

Fig. 4. Typical counterclockwise atrial flutter with characteristic sawtooth pattern of flutter waves.

is a question of anomalous AV conduction such as in WPW syndrome. The blockade of the AV node may permit conduction of electrical impulses unopposed down a rapidly anterograde conducting accessory pathway, which can result in VF.[45]

In some instances, the flutter wave can be reversed and result in a clockwise circuit in the right atrium, which gives rise to positive flutter waves in the inferior leads (II, III, and aVf) and a negative flutter in V1. It can be difficult to determine the circuitry in some instances of flutter, and perhaps a better descriptive term for these rhythms is noncavotricuspid isthmus dependent macro-reentrant atrial tachycardia. These rhythms can arise in the left atrium and may be quite complex, and can occur in the setting of prior ablation procedures or following cardiac surgery.[57] Management in the acute setting remains the same. Acute cardioversion of atrial flutter can require lower energies than are used for AF, and ibutilide can result in conversion to sinus rhythm in 38% to 76% of patients.[58]

Supraventricular Tachycardias

Among the SVTs there are essentially 3 types based on their anatomic origins: sinus node dependent (eg, sinus tachycardia, sinus node reentry, inappropriate sinus tachycardia); atrial dependent (eg, atrial flutter/fibrillation [see earlier discussion], atrial tachycardia); AV-node dependent (eg, AVNRT, AVRT [accessory pathway involved in circuit], junctional tachycardia).

For the patient presenting with a narrow complex tachycardia, the administration of an AV nodal blocking agent such as adenosine can prove useful both therapeutically and diagnostically. Adenosine would be expected to terminate (at least temporarily) SVTs that are AV-node dependent. Rarely will an automatic atrial tachycardia terminate with adenosine, and other non–AV-node dependent SVTs will be unmasked as the AV node is blocked, permitting visualization of the underlying atrial activity (**Fig. 5**).[59] Certain conditions may exist in the ICU patient that would interfere with adenosine usage. For example, methylxanthines have adenosine receptor antagonist activity and may render the patient less sensitive to adenosine. Adenosine must be used with caution in patients with reactive airway disease, as it can provoke bronchospasm. Dipyridamole can block adenosine transport back into the cell and can enhance the response to adenosine (**Fig. 6**).

AV-node dependent arrhythmias

AVNRT is much more common than AVRT. If these arrhythmias prove refractory to adenosine or if they recur after adenosine administration, further suppression may be needed. For either termination or suppression, nondihydropyridine calcium-channel blockers or β-blockers may be used. Digoxin is of limited utility because of its delayed onset of action. Use of these drugs is with caution in the patient with overt preexcitation. Nondihydropyridine calcium-channel blockers and β-blockers may destabilize the patient because of their potential hypotensive effects, and should not be used for acute conversion in the hemodynamically compromised patient. Primary antiarrhythmics can cause hypotension and may have proarrhythmic effects, and should be avoided unless AV nodal blocking agents are ineffective and cardioversion cannot be done. Potential antiarrhythmics that can be considered include amiodarone, sotalol, procainamide, flecainide, disopyramide, or propafenone.[60] For patients with depressed left ventricular function, amiodarone, β-blockers, and digoxin may be preferred.

Junctional tachycardia typically arises as a result of enhanced automaticity, and may occur in the ICU setting as a result of digitalis toxicity or excessive use of exogenous catecholamines. These inciting/exacerbating agents should be withdrawn.

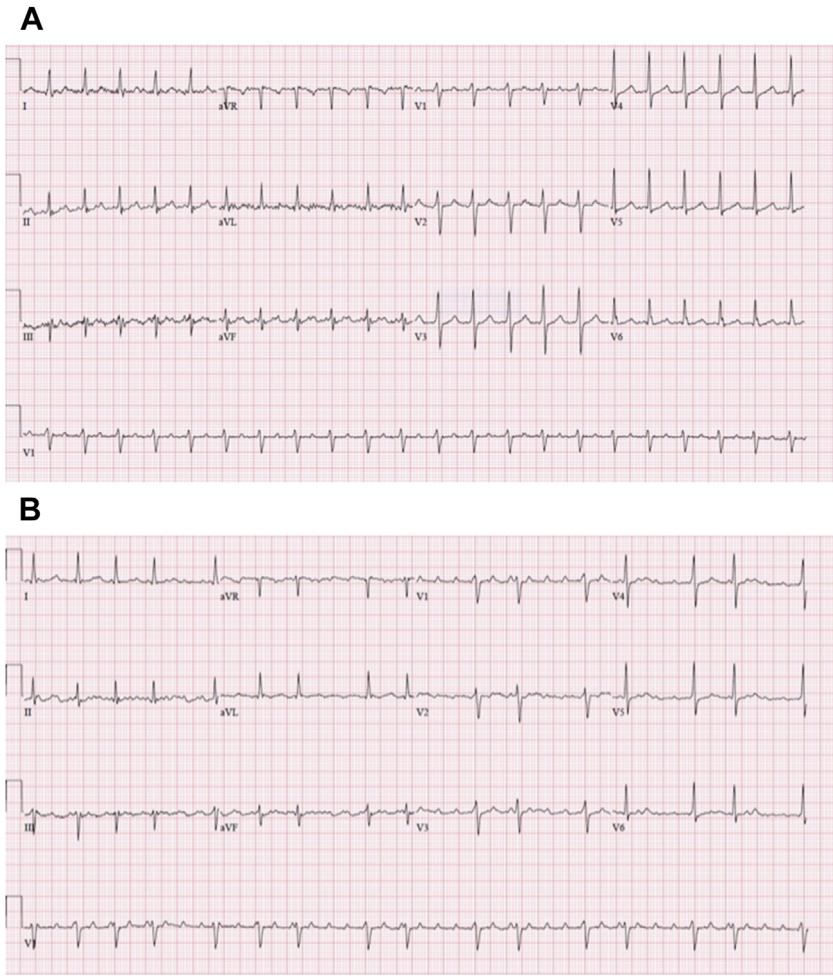

Fig. 5. (*A*) Narrow complex tachycardia of unclear mechanism. (*B*) After adenosine administration, underlying atrial tachycardia is unmasked.

Cardioversion is ineffective in converting junctional tachycardia related to increased automaticity, and may be harmful if the junctional tachycardia is caused by digitalis toxicity. If the arrhythmia persists despite removal of the inciting agents(s), the choice of medical therapy will depend on the underlying cardiac function. For patients with preserved ejection fraction, choices may include amiodarone, β-blockers, or nondihydropyridine calcium-channel blockers. For those with depressed function, amiodarone is preferred.

Atrial-dependent arrhythmia

A regular atrial tachycardia can occur from an ectopic atrial focus as a result of enhanced automaticity, and in the ICU setting this may be related to stimulant drugs used (eg, catecholamines) or to pulmonary disease. These arrhythmias are best treated by correcting the underlying cause, as cardioversion has no role. Before initiating specific treatment, it is important to determine whether there is any hemodynamic compromise related to the rhythm itself rather than the patient's underlying

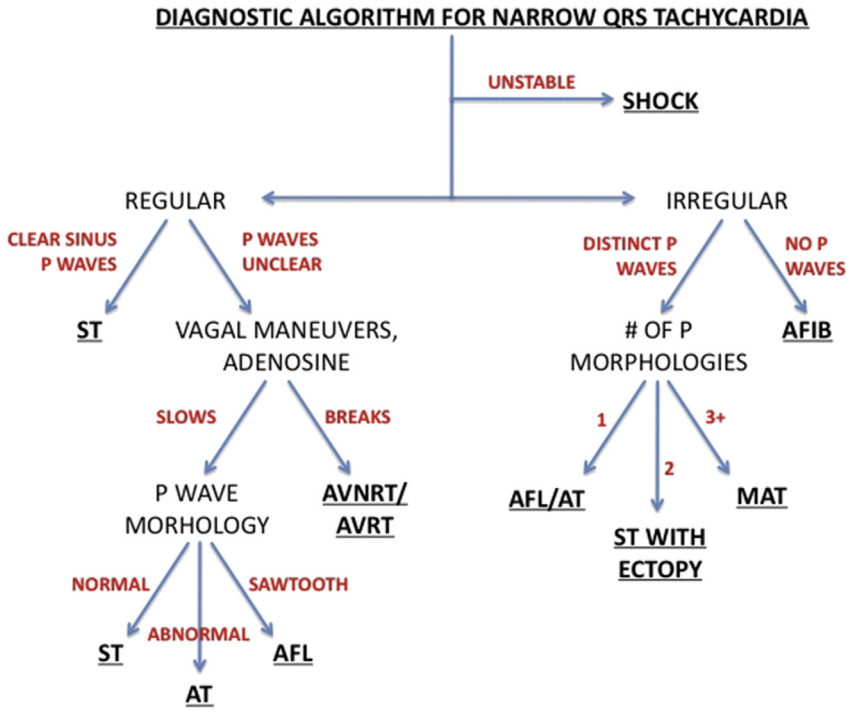

Fig. 6. Diagnostic algorithm for narrow QRS tachycardia. AFIB, atrial fibrillation; AFL, atrial flutter; AT, atrial tachycardia; AV, atrioventricular; AVNRT, AV nodal reentrant tachycardia; AVRT, AV reentrant tachycardia; MAT, multifocal atrial tachycardia; ST, sinus tachycardia.

medical condition. If drug therapy is deemed necessary, the choice of agent will be similar to that described earlier for AV nodal dependent arrhythmias, and will depend on the integrity of myocardial function and the presence or absence (and severity) of pulmonary disease. In the patient with preserved ejection fraction without other contraindications, amiodarone, nondihydropyridine calcium-channel blockers, or β-blockers may be used. In the patient with preserved ejection fraction, no absolute contraindications, and multifocal atrial tachycardia (MAT) (**Fig. 7**), the therapeutic options are the same.[61] MAT is typically associated with underlying pulmonary disease and is characterized by the identification of 3 or more separate P-wave morphologies in a rapid irregular rhythm. Medications may achieve clinical benefit as a result of their suppression of AV-node conduction and slowing of heart rate, rather than arrhythmia suppression. In patients with depressed ejection fraction, medication choices include amiodarone, β-blockers, and digoxin.

Sinus node–dependent arrhythmia

Sinus tachycardia occurs typically in response to the underlying medical problem, and correction depends on identifying and correcting possible causes (eg, fever, sepsis, pulmonary embolism, blood loss). Sinoatrial nodal reentrant tachycardia (SANRT) is a difficult diagnosis to make clinically. Technically this rhythm falls into the category of a macro-reentrant atrial arrhythmia involving the sinus node. Typical rates are in the range of 100 to 150 beats/min, and the P-wave is identical to that seen in sinus rhythm, often with underlying structural heart disease.[62,63] Like other reentrant arrhythmias, onset and offset are often abrupt, and episodes may last for hours.

Fig. 7. Multifocal atrial tachycardia characterized by multiple (≥3) P-wave morphologies.

Adenosine can terminate SANRT, and suppression can sometimes be achieved with verapamil or amiodarone.[64,65]

Wide Complex Tachycardias

Wide complex tachycardias can be of either supraventricular or ventricular origin. There are several well-published guidelines for electrocardiographic distinction that can be helpful (**Box 5**). When possible, it is extremely useful to obtain the baseline ECG to determine whether there is a preexistent conduction abnormality. In general, aberration of an SVT in a patient without an underlying conduction abnormality will electrocardiographically appear more like a typical bundle branch block morphology. In patients with an underlying conduction abnormality, the QRS complex will appear similar to the baseline morphology, but may be wider owing to rate-related conduction delays. Virtually any SVT with intact AV nodal conduction can result in a wide complex tachycardia. The presence of AV dissociation is a strong indicator that the rhythm is of ventricular origin.

In patients with WPW syndrome, the most common tachycardia is orthodromic AV reentry (electrical impulse traveling anterograde down the AV node and retrograde up the accessory pathway). In some patients with WPW syndrome, an antidromic AV reentrant arrhythmia can occur (down the accessory pathway and up the AV node) (**Fig. 8**). The ECG will appear wide and the morphology will not appear as a typical

Box 5
Wide complex tachycardia is more likely ventricular tachycardia if…

- Atrioventricular dissociation
- Very wide QRS (>160 milliseconds if left bundle branch block, >140 milliseconds if right bundle branch block)
- Bizarre QRS morphology
- Abnormal axis (“NW axis”)
- Concordance across precordial leads
- Capture beats
- Fusion beats

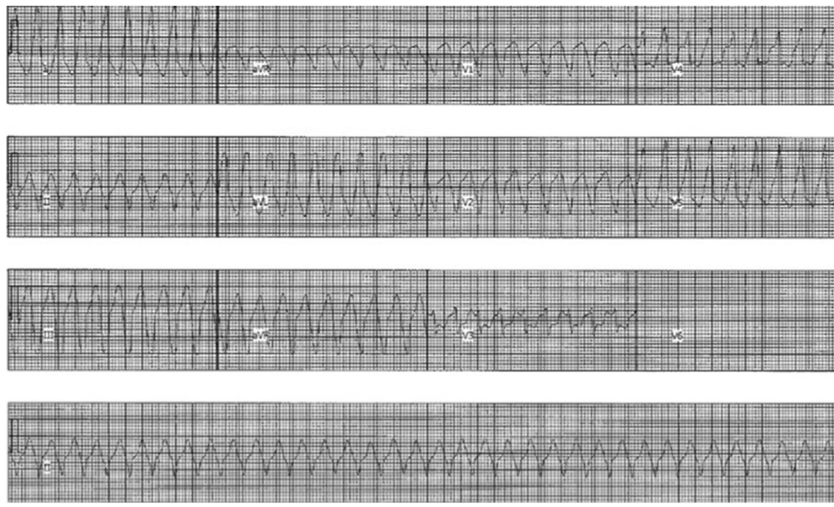

Fig. 8. Antidromic atrioventricular (AV) reentrant tachycardia with anterograde conduction via a posteroseptal accessory pathway and retrograde conduction via the AV node.

bundle branch block, and may be difficult to distinguish from VT. AF in the patient with WPW may appear wide and bizarre if anterograde conduction is present. A hallmark of preexcited AF is the capacity to (in some cases where the properties of the pathway permit) conduct at very rapid rates and to have varying morphologies as more, or less of the impulse travels anterograde to the ventricle down the accessory pathway.

In a patient with a cardiac implanted electrical device (pacemaker or defibrillator), a wide complex tachycardia can occur under a variety of situations, including (1) true superseding arrhythmia unrelated to the device or (2) device involvement in the rhythm. Examples of device-related tachycardias can include ventricular tracking of a rapid atrial rate (eg, AF, atrial flutter, or sinus tachycardia) or pacemaker-mediated tachycardia. The latter usually results when there is loss of atrial capture but intact ventricular capture, followed by retrograde atrial activation through an intact AV node and subsequent ventricular pacing based on the sensed atrial event. Most devices can be programmed to avoid or terminate these rapid rhythms, and application of a magnet will terminate pacemaker-mediated tachycardia. Device interrogation is critical to determining the nature of the rhythm and taking corrective steps.

The other major cause of wide complex tachycardia is, of course, VT which accounts for 80% of wide complex tachycardias.[66] Although there may be clinical clues as to whether the rhythm is of supraventricular, or ventricular origin, it is not wise to rely on the apparent stability of the patient to make the distinction. VT should be suspected in the patient with underlying heart disease, such as cardiomyopathy, prior myocardial infarction, or valvular heart disease. In the postinfarct patient, 90% of cases of wide complex tachycardia will be VT, and this should be considered the diagnosis of exclusion.[67] Despite several algorithms available for distinguishing VT from SVT, it is often difficult in the acute setting to determine the origin of wide complex tachycardias (**Fig. 9**).[68]

The acute management of the patient with wide complex tachycardia will depend on the clinical stability of the patient. Unless it is known with certainty that the patient has a preexisting conduction defect, and that the rapid rhythm is morphologically the same as the sinus ECG, adenosine should only be used with extreme caution. In

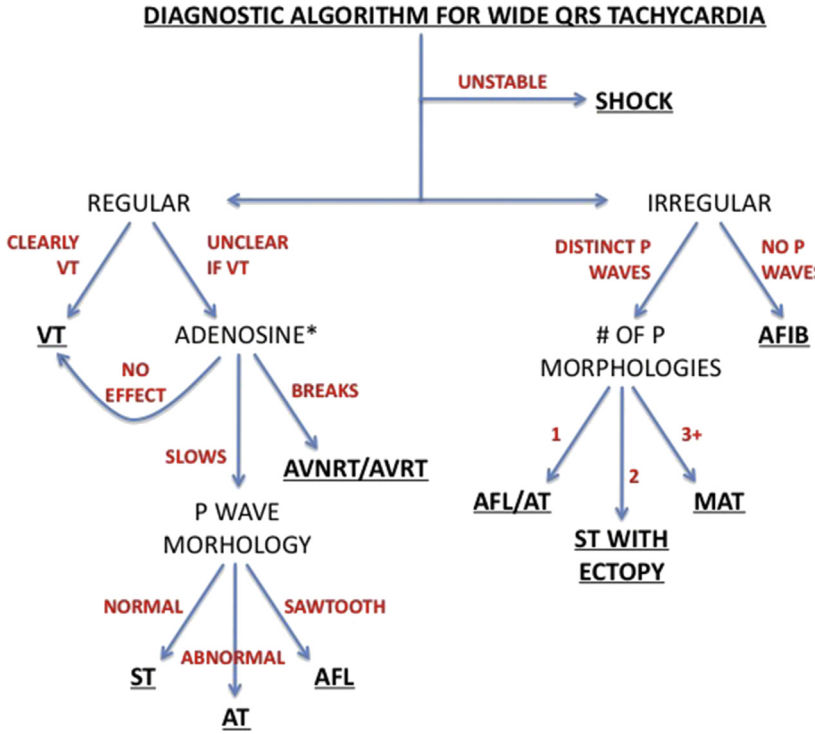

Fig. 9. Diagnostic algorithm for wide QRS tachycardia. AFIB, atrial fibrillation; AFL, atrial flutter; AT, atrial tachycardia; AV, atrioventricular; AVNRT, AV nodal reentrant tachycardia; AVRT, AV reentrant tachycardia; MAT, multifocal atrial tachycardia; ST, sinus tachycardia; VT, ventricular tachycardia. * Use caution with adenosine if there is possible VT.

preexcited arrhythmias (antidromic AVRT or preexcited AF), adenosine will not block the accessory pathway (and may even enhance its conduction) but may block the AV node, leaving anterograde conduction down the accessory pathway unopposed, and placing the patient at risk for degeneration to VF.[69] Patients with a wide complex tachycardia may appear hemodynamically stable, but the acute vasodilatory effect of adenosine may destabilize the patient in VT, and not terminate the abnormal rhythm.[70]

If the patient presents with hemodynamically stable wide complex tachycardia, use of an antiarrhythmic may be considered, recognizing that an apparently stable patient may decompensate rapidly either owing to the duration of the rhythm or to the hemodynamic effects of drugs. As with adenosine, drugs that are appropriate for SVT both diagnostically and for therapy such as β-blockers or nondihydropyridine calcium-channel blockers may cause rapid clinical deterioration in the patient with VT.[68] Acute administration of these drugs should be avoided in wide complex tachycardia of uncertain mechanism. If the patient is stable enough, steps should be taken to best determine the mechanism of the arrhythmia to better target the most appropriate treatment. Useful steps include evaluation of the baseline ECG, determining the likelihood of VT versus SVT with aberration based on the clinical history (assume VT in the postinfarct patient), determining prior episodes of arrhythmia, reviewing telemetry strips if available for prior nonsustained arrhythmias, and determining family history for potentially hereditary conditions such as WPW syndrome or channelopathies.

If the patient has hemodynamically unstable wide complex tachycardia, immediate steps should be taken toward cardioversion. Depending on patient stability, administration of analgesics or sedatives may be prudent. Extreme care must be taken to avoid clinical deterioration related to these drugs. Intravenous access, continuous monitoring, and supplemental oxygen should be in place before synchronous cardioversion. Although lower energies may convert atrial arrhythmias, it is the authors' practice to use higher energy levels immediately, rather than titrating upwards.

After initial stabilization, a thorough evaluation for underlying causes such as electrolyte imbalance, drug toxicity, ischemia, or catecholamine excess should be undertaken and remediable causes treated. In the event of recurrent VT or wide complex tachycardia of uncertain mechanism, antiarrhythmic therapy will likely be needed (Table 7). Amiodarone is typically the drug of choice (other than in cases of WPW) because of its superior efficacy. If WPW is suspected, procainamide may be an appropriate agent, as it can block the accessory pathway. Procainamide can be useful for SVT and VT, but its utility is limited by its tendency to induce hypotension. Lidocaine is also an appropriate agent but will not benefit most patients in whom the mechanism is SVT, owing to its lack of effect on atrial and AV nodal tissue. Lidocaine can slow or block accessory pathway conduction and can affect distal conduction.

Monomorphic VT

Most cases of monomorphic VT occur in the presence of underlying heart disease; the mechanism is typically reentry, as described earlier, and depends on discrepancies in conduction and refractoriness within the ventricular myocardium, usually in border zones of damaged and normal tissue. The characteristic appearance of this VT is of uniform QRS morphology. As with all arrhythmias, identification of underlying or exacerbating conditions is required. Similarly to the strategy described earlier, management is based on the stability or instability of the patient at the time of the arrhythmia. When drug therapy is needed, amiodarone and β-blockers are the preferred agents.[71,72] Lidocaine may also be used.[73] In general, agents that can compromise hemodynamics such as sotalol or intravenous procainamide should be avoided in the ICU patient unless the patient is completely hemodynamically stable. Long-term suppression depends on definitive correction, where possible, of reversible causes, and removal of inciting agents such as pressors.

Polymorphic VT

The hallmark electrocardiographically of PMVT is beat-to-beat variation in the QRS morphology. The mechanism of PMVT is different from monomorphic VT and is often hemodynamically unstable, and sustained episodes require urgent cardioversion.

Table 7
Drugs for wide complex tachycardia

Medication	Dose
Amiodarone	150 mg IV over 10 min, may repeat every 10 min as needed; then IV drip 1 mg/min for 6 h followed by 0.5 mg/min for 18 h (max. cumulative dose 2.2 g over 24 h)
Procainamide	15–18 mg/kg over 25–30 min or 100 mg given no faster than 50 mg/min, may repeat every 5 min (max. cumulative dose 1 g); then IV drip 1–4 mg/min
Lidocaine	1–1.5 mg/kg IV, may repeat 0.5–0.75 mg/kg every 5–10 min (max. cumulative dose 3 mg/kg); then IV drip 1–4 mg/min

PMVT may occur in the setting of either normal or long QT, and the baseline ECG should be evaluated to determine the QTc interval.

When seen in the setting of long QT, PMVT is termed torsades de pointes, and the approach is directed at correction of the QT (Fig. 10). Long QT can be hereditary or associated with several drug toxicities. In the setting of a congenital channelopathy associated long QT, torsades de pointes in more often associated with accelerated sinus rates with lengthening or inappropriate shortening of the QT interval. In acquired long QT torsades de pointes is often pause dependent, with further prolongation of the QT interval after the pause. In these instances, overdrive pacing and isoproterenol may be effective at arrhythmia suppression. Intravenous magnesium can also be effective at improving rhythm control in the patient with PMVT either with or without long QT, and correction of hypokalemia is critical.[74,75]

PMVT with normal QT is often associated with myocardial ischemia, which needs to be rapidly identified and corrected. This approach may require urgent cardiac catheterization and revascularization. Amiodarone and β-blockers may be effective for arrhythmia suppression.

Electrical Storm Recurrent VT/VF or ICD Discharges

Extreme electrical instability with recurrent episodes of VT or VF is infrequent and is typically seen in settings such as patients with acute myocardial ischemia or drug

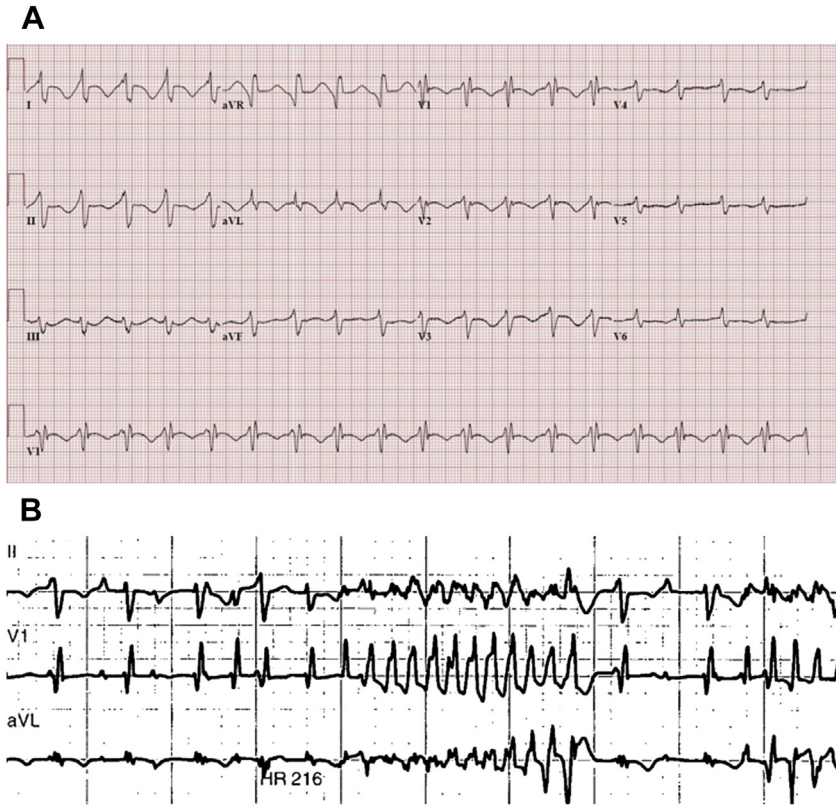

Fig. 10. (*A*) Sinus tachycardia with marked QT prolongation in a patient with Takotsubo cardiomyopathy. (*B*) Onset of torsades de pointes.

toxicity (including alcohol), and acute or worsened heart failure in patients with cardiomyopathy.[75,76] Less frequently, the patient will have an underlying primary electrical cause such as Brugada syndrome or long-QT syndrome. By definition, electrical storm exists when there are 3 or more episodes of VT or VF or appropriate discharges from an implanted cardioverter-defibrillator (ICD) in a 24-hour period.[75] As always, device interrogation is mandatory to ensure that the shocks are clinically appropriate and that the device is functioning normally. Among patients with implanted ICDs, the incidence of electrical storm may be 10% to 20%.[77] Gaining control of the arrhythmia is paramount given the potentially life-threatening nature of the arrhythmia itself, in addition to the potential long-term deleterious effects of multiple ICD therapies in the ICD patient population.[78]

The initial therapy is directed at identifying and correcting any potential underlying mechanism such as hypokalemia, other electrolyte imbalances, ischemia, worsening heart failure, or other remediable factors.[75] The pharmacologic agents that are most useful in electrical storm are amiodarone and β-blockers.[75,79] During cardiac arrest or electrical storms, the sympathetic nervous system is activated, and β-blockers are often very effective at suppressing recurrent VT/VF.[80] For the patient with an ICD, reprogramming the device to maximize attempts at pace termination rather than shocks, prolonging the time before ICD discharge, and other changes may be helpful acutely. For the ICD recipient who has repeated shocks despite optimization of medical therapy and device reprogramming, radiofrequency ablation may be considered, recognizing that the procedure is not without risk.[81]

In some cases, particularly where arrhythmia is pause dependent or in the setting of long QT, overdrive pacing with a temporary pacemaker may suppress the arrhythmia. The utility of isoproterenol for VT/VF suppression is limited to those patients with primary electrical abnormalities such as Brugada syndrome or long-QT syndrome.[82] Long-term management of the patient with electrical storm is directed toward maximizing therapy for heart failure, definitive ischemia correction through revascularization where feasible, and reducing risk for future events through optimization of electrolytes and other metabolic parameters.

Bradyarrhythmias

In the ICU setting, bradyarrhythmias are often the result of medical conditions, medications, or respiratory status (see earlier discussion on mechanisms). As such, many causes of bradycardia or heart block are anticipated to be reversible in the ICU setting. However, in situations where recurrent bradycardia is compromising the patient or impeding care, temporary pacing may be required. For very rare episodes of symptomatic pauses or if a definite need for transvenous pacing has not been established, external transcutaneous pacing is available. Another indication for transcutaneous pacing might be during right heart manipulation (eg, placement of right heart catheter) in a patient with an underlying left bundle branch block. Long-term or continuous transcutaneous pacing is not appropriate, as this form of pacing can be unreliable and painful.

Temporary transvenous right ventricular pacing can usually be accomplished at the bedside in the ICU without the use of fluoroscopy. If dual-chamber pacing is required (eg, patient does not tolerate right ventricular pacing, for overdrive suppression of atrial arrhythmias), placement of a right atrial lead is facilitated with the use of fluoroscopy.

Many postoperative cardiac patients will have epicardial leads placed at the time of surgery. A variety of temporary pacing electrodes are available for transvenous insertion, including a balloon-tipped catheter that is easiest for bedside insertion, but is

more likely to become dislodged and not optimal in the setting of cardiac arrest whereby forward flow is absent. Temporary screw-in leads are fairly reliable but require fluoroscopy for placement. Transvenous access from the right subclavian or internal jugular vein is preferred for ease of lead placement, patient comfort, and sterility. Careful site management is required to avoid contamination, and leads may be left in for 7to 10 days.

In the setting of acute myocardial infarction, temporary pacing is indicated for symptomatic bradyarrhythmias unresponsive to medical treatment.[83]

Special Circumstances: Patient with Ventricular Assist Device

The use of ventricular assist devices is becoming more common in patients with advanced heart failure, either as destination therapy or as a bridge to transplant. By definition, these patients are inherently at risk for arrhythmias related to their underlying cardiac disease, and the implantation of the assist device can create arrhythmic foci in the ventricle. Even though the presence of the assist device may mitigate the immediate compromise of a VA, left ventricular assist device flow may be decreased and contribute can contribute to mortality.[84] These patients may require advanced techniques for arrhythmia management, such as cryoablation or radiofrequency ablation.

SUMMARY

Cardiac arrhythmias are common in the ICU, and can be either the initial reason for admission to the ICU or a consequence of the medical condition. Exacerbating and contributing factors are multiple, and management of the patient requires a careful determination of these factors and correction where possible. Arrhythmias in the ICU are associated with short-term and long-term consequences. Such arrhythmias may occur in patients with underlying cardiac and pulmonary disease, but can occur in the medically ill or postoperative patient regardless of underlying pathology. A stepwise approach facilitates care.

1. Determine whether the patient is compromised by the arrhythmia as opposed to the underlying condition.
2. Aggressively manage life-threatening arrhythmias as per ACLS guidelines.
3. Determine the nature of the arrhythmia: what am I treating?
4. Determine underlying causes and identify correctable causes.
5. Determine appropriate drug therapy based on clinical condition.

REFERENCES

1. Tongyoo S, Permpikul C, Haemin R, et al. Predicting factors, incidence and prognosis of cardiac arrhythmia in medical, non-acute coronary syndrome, critically ill patients. J Med Assoc Thai 2013;96(Suppl 2):S238–45.
2. Annane D, Sébille V, Duboc D, et al. Incidence and prognosis of sustained arrhythmias in critically ill patients. Am J Respir Crit Care Med 2008;178(1):20–5.
3. Polanczyk CA, Goldman L, Marcantonio ER, et al. Supraventricular arrhythmia in patients having noncardiac surgery: clinical correlates and effect on length of stay. Ann Intern Med 1998;129(4):279–85.
4. Goodman S, Shirov T, Weismann C. Supraventricular arrhythmias in intensive care unit patients: short and long-term consequences. Anesth Analg 2007; 104:880–6.

5. Adekola OO, Soriyan OO, Meka I, et al. The incidence of electrolyte and acid-base abnormalities in critically ill patients using point of care testing (i-STAT portable analyser). Nig Q J Hosp Med 2012;22(2):103–8.
6. Volpi A, Cavalli A, Santoro L, et al. Incidence and prognosis of early primary ventricular fibrillation in acute myocardial infarction—results of the Gruppo Italiano per lo Studio della Sopravvivenza nell'Infarto Miocardico (GISSI-2) database. Am J Cardiol 1998;82(3):265.
7. Macdonald JE, Struthers AD. What is the optimal serum potassium level in cardiovascular patients? J Am Coll Cardiol 2004;43:155–61.
8. Whang R, Whang DD, Ryan MP. Refractory potassium repletion. A consequence of magnesium deficiency. Arch Intern Med 1992;152(1):40.
9. Ayres SM, Grace WJ. Inappropriate ventilation and hypoxemia as causes of cardiac arrhythmias: the control of arrhythmias without antiarrhythmic drugs. Am J Med 1969;46(4):495–505.
10. Jhanjee R, Templeton GA, Sattiraju S, et al. Relationship of paroxysmal atrial tachyarrhythmias to volume overload: assessment by implanted transpulmonary impedance monitoring. Circ Arrhythm Electrophysiol 2009;2:488–94.
11. Nuemar RW, Otto CW, Link MS, et al. Part 8: adult advanced cardiovascular life support. 2010 American Heart Association guidelines for cardiopulmonary resuscitation and emergency cardiovascular care. Circulation 2010;122: S729–67.
12. Ebert TJ, Hall JE, Barney JA, et al. The effects of increasing plasma concentrations of dexmedetomidine in humans. Anesthesiology 2000;93:382–94.
13. Hirose M, Carlson MD, Laurita KR. Cellular mechanisms of vagally mediated atrial tachyarrhythmia in isolated arterially perfused canine right atria. J Cardiovasc Electrophysiol 2002;13(9):918–26.
14. Gorgels AP, Vos MA, Smeets JL, et al. Delayed afterdepolarizations and atrial and ventricular arrhythmias. In: Rosen MR, Janse MJ, Wit AL, editors. Cardiac electrophysiology: a textbook. Mount Kisco (NY): Futura Publishing; 1990. p. 341.
15. Yap YG, Camm AJ. Drug induced prolongation and torsades de pointes. Heart 2003;89(11):1363.
16. De Ponti F, Poluzzi E, Cavalli A, et al. Safety of non-antiarrhythmic drugs that prolong the QT interval or induce torsades de pointes: an overview. Drug Saf 2002;25(4):263.
17. Jackman WM, Friday KJ, Anderson JL, et al. The long QT syndromes: a critical review, new clinical observations and a unifying hypothesis. Prog Cardiovasc Dis 1988;31(2):115.
18. Reinelt P, Karth GD, Geppert A, et al. Incidence and type of cardiac arrhythmias in critically ill patients: a single center experience in a medical-cardiological ICU. Intensive Care Med 2001;27(9):1466–73.
19. Camm AJ, Kirchhof P, Lip GY, et al. Guidelines for the management of atrial fibrillation: the Task Force for the Management of Atrial Fibrillation of the European Society of Cardiology (ESC). Eur Heart J 2010;31:2369–429.
20. Go AS, Hylek EM, Phillips KA, et al. Prevalence of diagnosed atrial fibrillation in adults: national implications for rhythm management and stroke prevention: the AnTicoagulation and Risk Factors in Atrial Fibrillation (ATRIA) Study. JAMA 2001;285:2370–5.
21. Kanji S, Williamson DR, Yaghchi BM, et al. Epidemiology and management of atrial fibrillation in medical and noncardiac surgical adult intensive care unit patients. J Crit Care 2012;27:326.e1–8.

22. Fioranelli M, Piccoli M, Mileto GM, et al. Analysis of heart rate variability five minutes before the onset of paroxysmal atrial fibrillation. Pacing Clin Electrophysiol 1999;22(5):743–9.
23. Herweg B, Dalal P, Nagy B, et al. Power spectral analysis of heart period variability of preceding sinus rhythm before initiation of paroxysmal atrial fibrillation. Am J Cardiol 1998;82(7):869–74.
24. Kannel WB, Wolf PA, Benjamin EJ, et al. Prevalence, incidence, prognosis, and predisposing conditions for atrial fibrillation: population-based estimates. Am J Cardiol 1998;82:2N–9N.
25. Wang TJ, Larson MG, Levy D, et al. Temporal relations of atrial fibrillation and congestive heart failure and their joint influence on mortality: the Framingham Heart Study. Circulation 2003;107:2920–5.
26. Krahn AD, Manfreda J, Tate RB, et al. The natural history of atrial fibrillation: incidence, risk factors, and prognosis in the Manitoba Follow-Up Study. Am J Med 1995;98:476–84.
27. Stewart S, Hart CL, Hole DJ, et al. A population-1 based study of the long-term risks associated with atrial fibrillation: 20-year follow-up of the Renfrew/Paisley study. Am J Med 2002;113:359–64.
28. Guyton AC. The relationship of cardiac output and arterial pressure control. Circulation 1981;64:1079–88.
29. Agency for Healthcare Research and Quality. Treatment of atrial fibrillation. Available at: http://effectivehealthcare.ahrq.gov/index.cfm/search-for-guides-reviews-and-reports/?productid=946&pageaction=displayproduct. Accessed May 9, 2014.
30. Kirchhof P, Andresen D, Bosch R, et al. Short-term versus long-term antiarrhythmic drug treatment after cardioversion of atrial fibrillation (Flec-SL): a prospective, randomised, open-label, blinded endpoint assessment trial. Lancet 2012;380:238–46.
31. Dunn AB, White CM, Reddy P, et al. Efficacy and cost analysis of ibutilide. Ann Pharmacother 2000;34(11):1233–7.
32. VerNooy RA, Mounsey P. Antiarrhythmic drug therapy in atrial fibrillation. Cardiol Clin 2004;22:21–34.
33. Gowda RM, Khan IA, Punukollu G, et al. Female preponderance in ibutilide-induced torsade de pointes. Int J Cardiol 2004;95(2–3):219.
34. Stambler BS, Wood MA, Ellenbogen KA, et al. Efficacy and safety of repeated intravenous doses of ibutilide for rapid conversion of atrial flutter or fibrillation. Ibutilide Repeat Dose Study Investigators. Circulation 1996;94(7):1613.
35. Li H, Natale A, Tomassoni G, et al. Usefulness of ibutilide in facilitating successful external cardioversion of refractory atrial fibrillation. Am J Cardiol 1999;84(9):1096–8, A10.
36. Clemo HF, Wood MA, Gilligan DM, et al. Intravenous amiodarone for acute heart rate control in the critically ill patient with atrial tachyarrhythmias. Am J Cardiol 1998;81(5):594.
37. Roy D, Talajic M, Dorian P, et al. Amiodarone to prevent recurrence of atrial fibrillation. Canadian Trial of Atrial Fibrillation Investigators. N Engl J Med 2000;342(13):913.
38. Danias PG, Caulfield TA, Weigner MJ, et al. Likelihood of spontaneous cardioversion of atrial fibrillation to sinus rhythm. J Am Coll Cardiol 1998;31:588–92.
39. Sleeswijk ME, Van Noord T, Tulleken JE, et al. Clinical review: treatment of new-onset atrial fibrillation in medical intensive care patients- a clinical framework. Crit Care 2007;11:233.

40. Miller S, Crystal E, Garfinkle M, et al. Effects of magnesium on atrial fibrillation after cardiac surgery: a meta-analysis. Heart 2005;91:618–23.
41. Delle KG, Geppert A, Neunteufl T, et al. Amiodarone versus diltiazem for rate control in critically ill patients with atrial tachyarrhythmias. Crit Care Med 2001;29:1149–53.
42. Cagli K, Ozeke O, Ergun K, et al. Effect of low-dose amiodarone and magnesium combination onatrial fibrillation after coronary artery surgery. J Card Surg 2006;21:458–64.
43. Kim RJ, Gerling BR, Kono AT, et al. Precipitation of ventricular fibrillation by intravenous diltiazem and metoprolol in a young patient with occult Wolff-Parkinson-White syndrome. Pacing Clin Electrophysiol 2008;31:776–9.
44. Blomstrom-Lundqvist C, Scheinman MM, Aliot EM, et al. ACC/AHA/ESC guidelines for the management of patients with supraventricular arrhythmias—executive summary. a report of the American College of Cardiology/American Heart Association Task Force on Practice Guidelines and the European Society of Cardiology Committee for Practice Guidelines (writing committee to develop guidelines for the management of patients with supraventricular arrhythmias) developed in collaboration with NASPE-Heart Rhythm Society. J Am Coll Cardiol 2003;42:1493–531.
45. Boriani G, Biffi M, Frabetti L, et al. Ventricular fibrillation after intravenous amiodarone in Wolff-Parkinson-White syndrome with atrial fibrillation. Am Heart J 1996;131:1214–6.
46. Hogue CW, Creswell LL, Gutterman DD, et al. American College of Chest Physicians guidelines for the prevention and management of postoperative atrial fibrillation after cardiac surgery: epidemiology, mechanisms, and risks. Chest 2005;128(Suppl 2):9S–16S.
47. Martinez EA, Epstein AE, Bass EB. American College of Chest Physicians guidelines for the prevention and management of postoperative atrial fibrillation after cardiac surgery. Pharmacological control of ventricular rate. Chest 2005; 128(Suppl 2):56S–60S.
48. Fuster V, Rtyden LE, Asinger RW, et al. ACC/AHA/ESC guidelines for the management of patients with atrial fibrillation: a report of the American College of Cardiology/American Heart Association Task Force on Practice Guidelines and the European Society of Cardiology Committee on Practice Guidelines and Policy Conferences. J Am Coll Cardiol 2001;38:1266i–1xx.
49. Camm AJ, Lip GY, De CR, et al. 2012 focused update of the ESC Guidelines for the management of atrial fibrillation: an update of the 2010 ESC Guidelines for the management of atrial fibrillation. Developed with the special contribution of the European Heart Rhythm Association. Eur Heart J 2010;31:2369–429.
50. Lip GY, Tse HF, Lane DA. Atrial fibrillation. Lancet 2012;379:648–61.
51. Mason PK, Lake DE, DiMarco JP, et al. Impact of the CHA2DS2-VASc score on anticoagulation recommendations for atrial fibrillation. Am J Med 2012;125:603–6.
52. Connolly SJ, Ezekowitz MD, Yusuf S, et al. Dabigatran versus warfarin in patients with atrial fibrillation. N Engl J Med 2009;361:1139–51.
53. Granger CB, Alexander JH, McMurray JJ, et al. Apixaban versus warfarin in patients with atrial fibrillation. N Engl J Med 2011;365:981–92.
54. Patel MR, Mahaffey KW, Garg J, et al. Rivaroxaban versus warfarin in nonvalvular atrial fibrillation. N Engl J Med 2011;365:883–91.
55. Pisters R, Lane DA, Nieuwlaat R, et al. A novel user-friendly score (HAS-BLED) to assess 1-year risk of major bleeding in patients with atrial fibrillation: the Euro Heart Survey. Chest 2010;138:1093–100.

56. Gelzer AR, Moise NS, Vaidya D, et al. Temporal organization of atrial activity and irregular ventricular rhythm during spontaneous atrial fibrillation: an in vivo study in the horse. J Cardiovasc Electrophysiol 2000;11:773–84.
57. Saoudi N, Cosio F, Waldo A, et al. Classification of atrial flutter and regular atrial tachycardia according to electrophysiologic mechanism and anatomic bases: a statement from a joint expert group from the Working Group of Arrhythmias of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology. J Cardiovasc Electrophysiol 2001;12:852–66.
58. Trappe H-J, Brandts B, Weismueller P. Arrhythmias in the intensive care patient. Curr Opin Crit Care 2003;9(5):345–55.
59. Camm AJ, Garratt CJ. Adenosine and supraventricular tachycardia. N Engl J Med 1991;325(23):1621.
60. Jordaens L, Gorgels A, Stroobandt R, et al. Efficacy and safety of intravenous sotalol for termination of paroxysmal supraventricular tachycardia. The Sotalol Versus Placebo Multicenter Study Group. Am J Cardiol 1991;68(1):35.
61. Kouvaras G, Cokkinos DV, Halal G, et al. The effective treatment of multifocal atrial tachycardia with amiodarone. Jpn Heart J 1989;30(3):301.
62. Gomes JA, Mehta D, Langan MN. Sinus node reentrant tachycardia. Pacing Clin Electrophysiol 1995;18(5 Pt 1):1045.
63. Garson A Jr, Gillette PC. Electrophysiologic studies of supraventricular tachycardia in children. I. Clinical-electrophysiologic correlations. Am Heart J 1981; 102(2):233.
64. Engelstein ED, Lippman N, Stein KM, et al. Mechanism-specific effects of adenosine on atrial tachycardia. Circulation 1994;89(6):2645.
65. Gomes JA, Hariman RJ, Kang PS, et al. Sustained symptomatic sinus node reentrant tachycardia: incidence, clinical significance, electrophysiologic observations and the effects of antiarrhythmic agents. J Am Coll Cardiol 1985;5(1):45.
66. Akhtar M, Shenasa M, Jazayeri M, et al. Wide QRS complex tachycardia. Reappraisal of a common clinical problem. Ann Intern Med 1988;109(11):905.
67. Tchou P, Young P, Mahmud R, et al. Useful clinical criteria for the diagnosis of ventricular tachycardia. Am J Med 1988;84(1):53.
68. Stewart RB, Bardy GH, Greene HL. Wide complex tachycardia: misdiagnosis and outcome after emergent therapy. Ann Intern Med 1986;104(6):766.
69. Garratt CJ, Griffith MJ, O'Nunain S, et al. Effects of intravenous adenosine on antegrade refractoriness of accessory atrioventricular connections. Circulation 1991;84(5):1962.
70. Sharma AD, Klein GJ, Yee R. Intravenous adenosine triphosphate during wide QRS complex tachycardia: safety, therapeutic efficacy, and diagnostic utility. Am J Med 1990;88(4):337.
71. Eifling M, Razavi M, Massumi A. The evaluation and management of electrical storm. Tex Heart Inst J 2011;38(2):111–21.
72. Naccarelli GV, Jalal S. Intravenous amiodarone. Another option in the acute management of sustained ventricular tachyarrhythmias. Circulation 1995; 92(11):3154.
73. Griffith MJ, Linker NJ, Garratt CJ, et al. Relative efficacy and safety of intravenous drugs for termination of sustained ventricular tachycardia. Lancet 1990; 336(8716):670.
74. Tzivoni D, Banai S, Schuger C, et al. Treatment of torsade de pointes with magnesium sulfate. Circulation 1988;77(2):392.
75. Zipes DP, Camm AJ, Borggrefe M, et al, American College of Cardiology/American Heart Association Task Force, European Society of Cardiology Committee

for Practice Guidelines, European Heart Rhythm Association, Heart Rhythm Society. ACC/AHA/ESC 2006 guidelines for management of patients with ventricular arrhythmias and the prevention of sudden cardiac death: a report of the American College of Cardiology/American Heart Association Task Force and the European Society of Cardiology Committee for Practice Guidelines (writing committee to develop guidelines for management of patients with ventricular arrhythmias and the prevention of sudden cardiac death): developed in collaboration with the European Heart Rhythm Association and the Heart Rhythm Society. Circulation 2006;114(10):e385.

76. Greene M, Newman D, Geist M, et al. Is electrical storm in ICD patients the sign of a dying heart? Outcome of patients with clusters of ventricular tachyarrhythmias. Europace 2000;2(3):263.
77. Emkanjoo Z, Alihasani N, Alizadeh A, et al. Electrical storm in patients with implantable cardioverter-defibrillators: can it be forecast? Tex Heart Inst J 2009;36(6):563–7.
78. Gatzoulis KA, Andrikopoulos GK, Apostolopoulos T, et al. Electrical storm is an independent predictor of adverse long-term outcome in the era of implantable defibrillator therapy. Europace 2005;7(2):184–92.
79. Kudenchuk PJ, Cobb LA, Copass MK, et al. Amiodarone for resuscitation after out-of-hospital cardiac arrest due to ventricular fibrillation. N Engl J Med 1999; 341(12):871–8.
80. Nademanee K, Taylor R, Bailey WE, et al. Treating electrical storm: sympathetic blockade versus advanced cardiac life support-guided therapy. Circulation 2000;102(7):742–7.
81. Aliot EM, Stevenson WG, Almendral-Garrote JM, et al. EHRA/HRS expert consensus on catheter ablation of ventricular arrhythmias: developed in a partnership with the European Heart Rhythm Association (EHRA), a Registered Branch of the European Society of Cardiology (ESC), and the Heart Rhythm Society (HRS); in collaboration with the American College of Cardiology (ACC) and the American Heart Association (AHA). Heart Rhythm 2009;6(6):886–933.
82. Ohgo T, Okamura H, Noda T, et al. Acute and chronic management in patients with Brugada syndrome associated with electrical storm of ventricular fibrillation. Heart Rhythm 2007;4(6):695–700.
83. O'Gara PT, Kushner FG, Ascheim DD, et al. 2013 ACCF/AHA guideline for the management of ST-elevation myocardial infarction: executive summary: a report of the American College of Cardiology Foundation/American Heart Association Task Force on Practice Guidelines. Circulation 2013;127:529–55.
84. Bedi M, Kormos R, Winowich S, et al. Ventricular arrhythmias during left ventricular assist device support. Am J Cardiol 2007;99(8):1151–3.